Understanding
Something About Nothing:
Radiation Zeros

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Radiation symmetry is briefly reviewed, along with its historical, experimental, computational, and theoretical relevance. A sketch of the proof of a theorem for radiation zeros is used to highlight the connection between gauge-boson couplings and Poincare transformations. It is emphasized that while mostly bad things happen to good zeros, the weak-boson self-couplings continue to be intimately tied to the best examples of exact or approximate zeros.

INTRODUCTION

There are radiation zeros all over the place. See Fig. 1. Almost all Born amplitudes for the radiation of photons and gluons and other massless gauge bosons have such zeros. One reason no one notices them, however, is that only a small fraction occur in physical regions of scattering or decay. See Fig. 2 later on.

The conditions for physical "null zones" are sufficiently restrictive that the first examples of radiation zeros (the Mikaelian-Samuel-Sahdev zeros [1]), were discovered only when radiative weak-boson production was analyzed. (Striking dips in the angular distributions of $\overline{\nu}e \to W\gamma$ and $q\overline{q} \to W\gamma$ corresponding to the zeros had been seen earlier. [2]) The zero in the $q\overline{q}$ channel has proven to be an important signature in testing the trilinear $WW\gamma$ couplings, as wonderful progress is drawing tighter and tighter bounds. So far, all are converging to the standard model predictions. [3] The progress has been accelerated by theoretical support by Baur, Errede, and Landsberg [4], showing that laboratory rapidity correlations involving the photon and the charged decay lepton display a pronounced dip if the radiation zero exists. In a very nice talk, Tao Han has shown us the details (and plots) at this conference. [5]

Additional history. Permit me to digress for a moment. Our original work [6,2] on the production of electroweak pairs in proton collisions

$$p\overline{p}, \; pp \to WW, ZZ, WZ, W\gamma \tag{1}$$

took place in the late 70's. This was presented as an alternative to electron colliders, betting that the necessary energy threshold would first be reached by proton machines. And the theoretical discovery of the first radiation zero came in the midst of looking at the corresponding Born calculations. So it is gratifying, after all these years, to be at the present conference where many experimental results, including those pertaining to the $W\gamma$ zero, have now been achieved.

In view of the role of the $W\gamma$ channel, I have been given the opportunity to review the theory of the radiation zero, and to connect it to another signature of interest, "approximate" zeros. Owing to the fact that out of all the people from all the old collaborations from CWRU, Oklahoma State, Wisconsin, and SLAC, I happen to be the only one present means I have some responsibility to mention the early work.[1] This is also a welcome chance to talk about a theoretical development that, because of the lack of examples, is not well known, but perhaps should be. Continuing experimental progress provides a good incentive.

In particular, I would like to emphasize a picture that emerges in the proof of general radiation zero theorems. The emission, or absorption, of a gauge boson can be viewed as a local Lorentz transformation (or better, a Poincare transformation) of the particle doing the emitting or absorbing. This may be of importance in future model building, especially since our only successful theories to date, gauge theories, lead to universal forms for this transformation.

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[1]I was asked by a young CWRU graduate student whether this meant all the others had passed away.

FIG. 1. Even in the early days of QED, zeros could have been found.

RADIATION INTERFERENCE THEOREMS

It seems to me that the experimental, computational and theoretical consequences of radiation zeros and their generalizations are easiest to describe if we first look at an archetypal theorem for their existence and location. The classical limit of such zeros will also be evident. The primary example of the general set of radiation zero theorems found by Brodsky, Kowalski, and meeski [7,8] is for the emission of single photons.

Single-photon theorem

The theorem is the following. Consider the quantum amplitude M_γ for the emission of a single photon with momentum q. Besides the photon, assume there are n other particle legs (k particles in and $n-k$ particles plus γ out, say). The theorem is that the tree amplitude approximation vanishes, independent of anybody's spin, for common charge-to-light-cone-energy ratios, viz.

$$M_\gamma(tree) = 0$$
$$\text{if } \frac{Q_i}{p_i \cdot q} = \text{same, all } i \tag{2}$$

where the ith particle has electric charge Q_i and four-momentum p_i. The stipulations are that all couplings must be "gauge-theoretic". That is, the photon couplings to the particles must be as prescribed by local gauge theory, and any derivative couplings among the particles themselves must be gauge covariant. Also, scalar, spinor, and vector particles can be accommodated (spins ≤ 1). We return at the end to the question of higher spins.

Physical null zones

The factors $\frac{Q_i}{p_i \cdot q}$ come from the coupling and particle propagator denominator. It is easy to go into the complex plane to make them equal, and hence zeros are all over the (complex) place. But for them to be equal in physical phase space, the first and obvious requirement is that all charges must have the same sign (since $p \cdot q \geq 0$). This knocks out many reactions. By the way, there are only $n - 2$ independent equations. Interestingly and importantly, the last ratio is automatically the same if the rest are equal, by virtue of charge and momentum conservation.[2]

In the garden variety reactions, we could look, for example, at electron-electron bremsstrahlung, $e^- e^- \to e^- e^- \gamma$. The Born amplitude vanishes if the photon is at right angles to the c.m. beam direction, and the final electrons have the same energy. The null zone is two-dimensional, and the reason this radiation zero was not noticed in radiative corrections calculations is that the final-state phase space is sufficiently high dimensional.

Relevance

EXPERIMENTAL The null zone conditions explain why it took so long to discover radiation zeros. *We had to wait for fractionally charged quarks and weak bosons in order to get three things: Same-sign fermion-antifermion pairs, a process well-approximated by a Born amplitude, and only three particles plus the photon so the null zone was simple.* The amplitude for $q\overline{q} \to W\gamma$ vanishes at a photon scattering angle determined by the quark charges. (The $\nu\overline{e} \to W\gamma$ amplitude vanishes at the edge of phase space and is easily misinterpreted as a helicity constraint.) The corresponding null zone in radiative W decay [9] is a line in the Dalitz plot.

The first is still the best example. Again, I can refer to Tao Han's talk, but the relevance is that only for the very restrictive couplings coming out of gauge theory does the zero occur. In view of the results of many calculations with anomalous couplings, and the proof (see below) of the pertinent theorem, I do not think it would be hard to put together another theorem. Accepting the present particle content of our world, *only in the standard electroweak theory will there be a zero in the $W\gamma$ reaction.* In any other theory including composite models the rapidity dip will get filled in. We say such experiments test gauge theories and test the electromagnetic properties of weak bosons.   :)

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[2]What I'm saying is, if you have 10% rotten apples and 10% rotten oranges, then the overall percentage of rotten fruit is the same 10%.

What about other photonic zeros? The aforementioned zero in electron-electron bremsstrahlung is less interesting as a test, and involves more particles. There has been work on electron-quark and quark-antiquark bremsstrahlung, as tests of quark properties, but these lead to jet identification experiments, along with the more complicated phase space. [10–13] We will come back to the subject of more tests of weak-boson properties in a bit. :|

But as noted most zeros are unphysical. :(

COMPUTATIONAL As a by-product of the general proof of radiation zeros, we learn how to rewrite the set of Feynman tree diagrams as a smaller number of factored terms, separately gauge-invariant. It is possible to combine the CALKUL photon polarization vectors, for which the fermionic degrees of freedom are used as the bases, and very much simplify the amplitude analysis.

The radiation symmetry may be used, as gauge invariance is used, to check the increasingly laborious calculations used in higher-order perturbation theory studies. There is an analogous non-Abelian radiative symmetry that exists to check QCD jet calculations, for example.

THEORETICAL The mechanism in the radiation zero phenomena that has rather uniquely shown itself is the relation between a photon coupling and local Poincare invariance. We repeat that only gauge theory couplings lead to universal space-time transformations, and it is of value to sketch the proof in order to see how this connection is exposed and what universality means.

PROOF HIGHLIGHTS

We can describe the proof fairly succinctly in terms of photon attachments in a minute. But first let us lay some groundwork.

Vertex source graphs

Define a "source" graph T_G with which we will generate the complete tree radiation amplitude by the attachment of a photon in all possible ways. After simplification of the product of vertex and propagator for the attachment of a photon to a given leg, the complete tree for a source graph V_G made up of a single vertex (no internal lines) is

$$M_\gamma(V_G) = \sum \frac{Q_i J_i}{p_i \cdot q} \tag{3}$$

where we see the $Q/p \cdot q$ factors emerge from the coupling and propagator denominator. The coefficient "vertex current" J_i is the result of inserting the current j_i into the ith leg, with

$$j = j_{conv} + j_{spin} + j_{cont} + j_{YM} \tag{4}$$

The convection current is $p \cdot \epsilon$,[3] the spin current is a first-order momentum-space Lorentz transformation of the wave function (e.g., $\frac{i}{4}\sigma^{\alpha\beta}\omega_{\alpha\beta}$ for a spinor), the contact current is the corresponding transformation of single derivative couplings and the Yang-Mills current has the form of $\omega_{\mu\nu} \times$ (the q terms in the Yang-Mills vertex). The first-order Lorentz parameter tensor is

$$\omega_{\mu\nu} = q_\mu \epsilon_\nu - \epsilon_\mu q_\nu \tag{5}$$

where ϵ is the photon polarization vector.

The key identity is that the sum over the vertex currents is zero

$$\sum J_i = 0 \tag{6}$$

because the sum over the convection currents vanishes by momentum conservation, the sum over the combination of spin currents and contact currents vanishes by Lorentz invariance, and the sum over the Yang-Mills current vanishes by the Bianchi identity. Equal $Q/p \cdot q$ factors can be pulled out of the sum Eq.(3) and the complete radiative process for a vertex source graph vanishes by Eq.(6).

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[3]Sign changes in going from final to initial legs are left understood throughout these formulas.

Allowed couplings

The vertex graph could have involved any number of particles, but the universal forms of the various currents j_i are preserved only if there are important restrictions on any derivative couplings present. There can be no derivatives of Dirac fields; single derivatives of scalar fields are allowed; single derivatives of vector fields and double derivatives of scalar fields are allowed but only in Yang-Mills trilinear form (reminding us of the relationship between the longitudinal vector boson and the Goldstone bosons in spontaneous symmetry breaking). And the photon couplings also must follow the gauge algorithm: All derivatives are replaced by covariant derivatives.

Connection to space-time symmetry

A succinct way of looking at the previous result is that the attachment of a photon generates transformations. The convection current corresponds to a (first-order) displacement of that leg's wave function, the spin current to its Lorentz transformation, and the contact current to a Lorentz transformation of the derivative coupling. For common $Q/p \cdot q$, all these transformations correspond to the same universal element and they cancel by invariance. The photon attachment is a first-order Poincare transformation on the vertex amplitude, but by the invariance of that amplitude, it becomes "unattached" in the null zone.

General source graphs

To finish the proof, consider general tree source graphs T_G with (fixed) internal lines. In tacking a photon in all possible ways onto the source graph, the new ingredient is internal line attachment. But there are Ward-like identities[4] that simplify the problem and are of the generic form (D denotes propagators)

$$D(p-q)\Gamma D(p) + (\text{seagulls, if any}) = D(p-q)j\frac{Q}{p \cdot q} + \frac{Q}{p \cdot q}jD(p) \tag{7}$$

Note that we get exactly the same kind of $\frac{Q}{p \cdot q}j$ factor for each internal leg of each vertex that we had for the external legs. Furthermore, in the null zone the internal ratio $\frac{Q}{p \cdot q}$ will equal the common external ratio by the same rotten fruit calculation described earlier. These identities have reduced the problem to a sum of vertex-source problems, and by the earlier arguments, the null zone applies to all trees.

Gauge invariant reorganization of Feynman diagrams

The result of applying the decomposition identities and the contracted forms of the external leg attachments is a new reduced and rearranged amplitude, a sum over vertices

$$M_\gamma(T_G) = \sum M_\gamma(V_G)R(V_G) \tag{8}$$

with the vertex attachments separated out from the rest of the graph factors R. Each term in the sum is separately gauge invariant. The radiation zero is evident from the fact that each factor $M_\gamma(V)$ vanishes in the null zone.

Alternate theorem. Notice that charge conservation $\sum Q_i = 0$ is dual to Eq.(6) and implies

$$M_\gamma(T_G) = 0 \quad \text{if} \quad \frac{J_i}{p_i \cdot q} = \text{same} \tag{9}$$

This alternate interference theorem refers to zeros that, by contrast, are spin-dependent but independent of charge.

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[4]For a scalar line, the identity is the same as the Ward identity.

Radiation symmetry and representation

Both theorems can be stated as symmetries. [14] They correspond to invariance under either replacement,

$$\frac{Q_i}{p_i \cdot q} \to \frac{Q_i}{p_i \cdot q} + C \ \ \text{or} \ \ \frac{J_i}{p_i \cdot q} \to \frac{J_i}{p_i \cdot q} + C' \tag{10}$$

By the appropriate choice of C and C', all zeros can be made explicit in a "radiation representation" for the vertex amplitudes:

$$M_\gamma(V_G) = \sum p_i \cdot q \left(\frac{Q_i}{p_i \cdot q} - \frac{Q_j}{p_j \cdot q}\right)\left(\frac{J_i}{p_i \cdot q} - \frac{J_k}{p_k \cdot q}\right) \tag{11}$$

for $i \neq j, k$. This reduces $M_\gamma(T_G)$ to a single factored form for the simplest case, $n = 3$, in agreement with the original work by Goebel, Halzen and Leveille. [15,16] Their beguiling statement for the original $q\bar{q} \to W^\pm\gamma$ is that the three Feynman amplitudes reduce to the sum of two Abelian (QED-like) diagrams multiplied by a factor in which the zero is explicit.

MULTI-PHOTONS AND GENERAL DECOUPLING THEOREM

What about neutrals amongst the n particles, including other photons? The quick answer from an examination of the $Q/p \cdot q$ factor is the right one. All neutral particles must be massless and travel in the same direction as the photon. Strictly, in the proof we must have the corresponding current J_i vanish in the null zone, and this is what is found.[5]

In fact, the multiphoton zeros and the connection to local Poincare transformations follow from a decoupling theorem [17,18] for the scattering of a system of particles immersed in an external electromagnetic plane wave. On the way to the theorem it is first shown that for a particle coupled to an external electromagnetic plane wave the wave functions for spins 0, 1/2, 1 all can be written in the form

$$\Psi(x) = ULT\chi(x) \tag{12}$$

where χ is the free solution. The U,L,T are local gauge, Lorentz, and displacement transformations, respectively, whose first-order terms are exactly the ones we have been talking about.

The identity used to show that these are indeed solutions ends up being a cornerstone to the whole radiation zero business. It is

$$(UT)^{-1}D^\mu UT = \Lambda^{\mu\nu}\partial_\nu \tag{13}$$

in which D is the covariant derivative (hiding the plane wave inside it) and Λ is the finite Lorentz transformation (little group element, actually) corresponding to ye olde ω. *It is observed that the plane wave has been swallowed up into a local space-time symmetry of the equation of motion.* The Λ terms go away by invariance, and isn't this familiar by now?

To finish the story of the theorem, consider the tree amplitude for the scattering of a system of particles with no external field. If we turn on an external electromagnetic field, the internal and external legs of the tree amplitude are altered according to the Fourier transforms of the ULT factors. In the null zone, all factors collapse to unity from charge conservation, Lorentz invariance, and momentum conservation. I have not done justice to the whole story, but the bottom line is that, like Perseus, the system of particles can be invisible to an external plane wave in special regions of phase space.

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[5]For very special cases, like Compton amplitudes, there are no radiation zeros, physical or non-physical, if the null zone corresponds to forward scattering of massless neutral vector particles.

FIG. 2. But most zeros are not in the physical phase space.

WHEN BAD THINGS HAPPEN TO GOOD ZEROS

Like some other recently well-publicized evidence, measurements of radiation zeros are destined to be contaminated, compromised and ultimately corrupted. See Fig. 2. To start with, higher-order corrections will not vanish in the null zone. The internal factors $Q/p \cdot q$ in closed loops correspond to momenta p that is integrated over; these factors are certainly not fixed by the outside legs. *It is interesting, however, that radiation symmetry Eqs.(10) still hold for the complete quantum amplitude to all orders in perturbation theory.*

Anomalous photon couplings spoil the zeros in lowest order. Many speakers at this conference have focused on limits that can be set on the κ and λ parameters for both $WW\gamma$ and WWZ trilinear couplings. As indicated by the earlier remarks, the $W\gamma$ zero provides litmus tests for these parameters. Any deviations from the gauge theory values lead to momentum dependence in the photon attachment currents such that the first-order transformations can no longer be universal.

Higher derivatives than the ones announced as "gauge-theoretic" produce terms in the J currents that are higher order in q. These terms have *a priori* no mechanism, no additional symmetry to effect their cancellation in a sum over all the legs of a given vertex. The Yang-Mills $\mathcal{O}(q^2)$ is the one exception that proves the rule.

Generalization to a Larger Gauge Sector

There are zeros associated with any gauge group when the corresponding massless gauge bosons are emitted. The "charges" now are the Clebsch-Gordan coefficients coming from the attachment of a boson belonging to the adjoint representation of the gauge group. The bad things here are two-fold. In QCD, color charges are averaged or summed over in hadronic reactions. The zeros are for the most part washed out, even when perturbation theory is applicable (in deep inelastic reactions, and so forth). In thinking of the weak bosons themselves, electroweak symmetry is broken. *Radiation zeros require the internal symmetry to remain good: The charges " Q_i " must be conserved.* Of course, the weak-boson masses are far from vanishing; a nonvanishing q^2 itself ruins radiation interference.

It is not surprising that in a supersymmetric or extended supersymmetric world, the photonic zeros would have partner photino zeros and "sphotino" zeros. There are "szeros" and "xeros" in the supersymmetrically extended gauge sector. [19,20] The well-known problem is that SUSY is experimentally evasive and hardly unbroken.

RECENT WORK

An "approximate zero" in WZ production by fermion-antifermion annihilation has been proposed recently by Baur, Han and Ohnemus [21,5] as another test of the self-couplings. At high energies, the sensitivity to the WWZ vertex is not so terribly different than that of the $W\gamma$ channel on the $WW\gamma$ vertex. It was briefly noted in the early, detailed paper on radiation zeros [8] that the dip structure found [2] in the WZ angular distributions corresponds to an approximate radiation interference zero. Baur *et al.* show that even in the high-energy limit there is a nonvanishing longitudinal helicity amplitude. Even if the c.m. energy is large compared with the masses, the couplings still refer to a broken symmetry theory and the zero will remain approximate at high energy. The approximate zero corresponds to broken radiation symmetry, nevertheless, and the origin and mechanism for the partial cancelations are the same as for the exact zeros.

Some day, experiments on multiboson zeros, exact or approximate, will make sense. Recent discussions of multi-photon/gluon reactions [22,23] could be extended to the broken symmetry weak-boson production channels. In WZZ production, for example, quadrilinear couplings come into play, along with a multi-Z approximate zero. But whether these couplings can be probed, even in the next generation of colliders, is very much open to question.

RIGHT AND LEFT

What is right

It may seem reasonable to say that the radiation zero phenomena are well understood. Among other things, they are another property of gauge theories. We have the following nice connections.

Classical interference. The zeros are the generalization of the well-known vanishing of classical nonrelativistic electric and magnetic dipole radiation occurring for equal charge/mass ratios (indeed, the low-energy limit of the null zone conditions!) and gyromagnetic g-factors. The null zone is exactly the same as that for the completely destructive interference of radiation by charge lines (a classical convection current calculation [8]) and is preserved by the fully relativistic quantum Born approximation for gauge theories.

Gauge couplings as transformations. Proving radiation symmetry theorems has brought forth the fact that gauge boson couplings to particles, including self-couplings, can be interpreted as transformations of the particles in both internal and external space. This is understandable since the gauge bosons belong to adjoint representations of both the Lie gauge groups and the Poincare space-time group. Only for the gauge couplings, however, do we get the universal Poincare generator representation by the spin and contact currents, which are necessary for radiation symmetry. For the SUSY and extended SUSY cases, we generate universal local supersymmetry and chiral transformations, respectively.

The long and the short of it. We have noted that the gauge-theory Born amplitudes have the same null zone as the classical radiation patterns. In the short-distance limit, gauge theories can be renormalized, corresponding to good high-energy behavior for the Born amplitudes. Thus, only for couplings that correspond to $g = 2$, for example, do both the short and long distance behaviors fall into these special categories. (Brodsky and Schmidt [24] emphasize the magic of $g = 2$, including its implications for photoabsorption sum rules.) We have this connection between the small and large distance scales.

What is left

Still, there are to me, at least, some loose ends.

Spin barrier. It has not been possible to find a theory of photon couplings, for instance, to particles with spins greater than one that preserves radiation symmetry. I at least have failed thus far in attempts to use supermultiplets in the gauge and matter sectors motivated by supersymmetry and string theories. Passarino tells how gravitons spoil radiation symmetry, and how their radiation does not seem to have any analogous zeros. [25] One way of describing this theoretical wall is in terms of a power series in photon momentum. (modulo the $Q/p \cdot q$ factor). The zeroth and first order terms are controlled by translation and Lorentz symmetry, respectively. The isolated instance of second-order terms in the Yang-Mills source vertex is controlled by the Bianchi identity, reminiscent of a curved-space-time symmetry. Higher spins lead to additional second-order and higher-order terms for which there must be new symmetries controlling them.

Mixing internal and external spaces. The null zone is defined by equations mixing internal charges and phase space. The original $W\gamma$ zero occurs at angles given in terms of quark charges. Radiation symmetry can be rewritten $Q_i \rightarrow Q_i + Cp_i \cdot q$. The mixing together of internal and external parameters suggests a look at ideas such as those behind Kalusza-Klein theories where a fifth or higher dimension is defined in terms of charges and gauge fields. The radiation symmetry could be part of the larger space-time symmetry, and radiation zeros a decoupling of the extra coordinate(s).

ACKNOWLEDGMENT

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